Zn Indiffusion Waveguide Polarizer on a Y-Cut LiNbO$_3$ at 1.32-μm Wavelength

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***Abstract*—A polarization-dependent loss measurement of Zn indiffusion (ZI) waveguide on a Y-cut LiNbO$_3$ substrate is firstly reported. The measured results show that the waveguides support either a single extraordinary polarization or both extraordinary and ordinary polarizations depending on the fabrication process parameters. For the single extraordinary polarization waveguide, the measured propagation loss at 1.32-μm wavelength is 0.9 dB/cm and the best measured polarization extinction ratio is 44 dB at a distance of 1.5 cm from the input end, which are quite good for being a waveguide polarizer. Moreover, the voltage-length product measured for the ZI Mach–Zehnder modulator shows that the substrate electrooptic coefficient is not degraded.**

***Index Terms*—Lithium niobate, polarization-dependent loss measurement, polarizer, Zn indiffusion.**

I. INTRODUCTION

SINGLE polarization waveguides are widely used for the fabrication of integrated optical sensors because a single polarization wave is essential to increase the optical sensitivity [1]. Moreover, a combination of a single and both polarization waveguides can be a polarization splitter with large splitting extinction ratio and fabrication tolerance [2]–[4]. To date, metal-clad Ti indiffusion (TI) and proton-exchange (PE) are two well-known methods for making single polarization waveguides on LiNbO$_3$ [5], [6]. In the metal-clad waveguide, the TM-wave propagation attenuation, depending on the buffer layer thickness and chosen metal-clad, is much larger than that of the TE-wave. After propagating a certain distance, only the TE-wave is left in the waveguide and it will be slightly affected by the cladding layers. As to the PE waveguide, the change in the extraordinary index Δn_e is positive while the change in the ordinary index Δn_o is negative. Thus, it supports only an extraordinary polarization wave. An annealing process is often used to reduce the propagation loss and restore the electrooptic coefficients. Therefore, good-performance devices have been successfully demonstrated on the z- and x-cut substrates [6], [7]. However, proton-exchanged waveguides suffer from surface damages and the guiding properties are consequently degraded on y-cut substrates [8]. This may cause serious problems in surface-wave acoustic-optical applications, since surface acoustic wave devices frequently require y-cut substrates. Although a tunable PE directional coupler with a SiO$_2$ cladding and thermal annealing has been demonstrated on a y-cut substrate at 0.6328-μm wavelength by Lee *et al.* [9], it is still difficult to fabricate a well confined waveguide at the near-IR wavelength region due to the PE depth and concentration limitations for avoiding surface damage.

Recently, Zn indiffusion (ZI) waveguides have been studied extensively to make optical devices in LiNbO$_3$ due to less susceptibility to photorefractive damage in comparison to TI waveguides [10]. Also, the Zn atoms have larger diffusion coefficients than those of the Ti atoms. Therefore, Zn diffusion needs no additional out-diffusion suppression and saves the time for diffusion, which provides flexibility for the fabrication of optical waveguides. The guiding characteristics at 0.6328-μm wavelength of a planar waveguide have been discussed [10], [11]. However, the variations of guided mode profiles and the polarization-dependent losses of a channel waveguide fabricated with different process parameters have never been addressed at the 1.32-μm wavelength.

In this paper, the polarization-dependent loss measurements of ZI waveguides on a y-cut, x-propagation LiNbO$_3$ substrate are demonstrated. The results show that the ZI waveguide supports a single extraordinary or both extraordinary and ordinary polarizations depending on process parameters. In such single extraordinary polarization waveguide, the propagation loss is 0.9 dB/cm and the best polarization extinction ratio measured at a distance of about 1.5 cm away from the input end of the waveguide is 44 dB. Therefore, it is quite suitable for using as a waveguide polarizer. Moreover, the fabricated ZI Mach–Zehnder modulator shows that it has a nondegraded electrooptic coefficient r_{33}. On the y-cut substrate, a ZI waveguide polarizer has the advantage of better performance and simpler fabrication process than that of a PE or a metal-clad TI waveguide polarizer.

II. EXPERIMENTS

First, a Zn thin film is deposited on the substrate by thermal evaporation. As Zn atoms are difficult to be leeched directly on the surface of LiNbO$_3$ substrate, a 50-Å Ni film is predeposited onto the LiNbO$_3$ substrate in order to increase the adhesion. A channel waveguide and a Mach–Zehnder modulator patterns are then formed by the lift- off technique. The waveguide width is 8 µm, the Y-branch angle is 2°, and the gap between two arms of the Mach–Zehnder modulator is 16 µm. The samples were placed on a covered alumina crucible, which was then placed in a high-temperature oven. The thermal cycle, which is carried out in dry air, typically involves heating at a rate of about 10 °C/min up to the diffusion temperature, maintaining at that temperature

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for a certain time, and cooling at a rate of 10 °C/min down to the room temperature.

After the thermal diffusion, the substrate end faces are cut and polished to allow end butt coupling. A schematic diagram of the polarization-dependent loss measurement setup is shown in Fig. 1. A He-Ne laser of wavelength 0.6328 μm is used for optical alignment. The polarization of an incident Nd:YAG laser light of wavelength 1.32 μm is controlled by rotating the polarizer. The angle is varied from 0° to 360° relative to the y-axis with a step of 10°. The incident light is in the TM polarization when the angle is set at 0° or 180°, and in the TE polarization, when the angle is set at 90° or 270°. For comparison, an attenuator is used to keep the incident power constant at different polarizations. The light is divided into a reference and a measurement light after passing through the beam splitter. The measurement light is coupled into the front end face of the waveguide with a 40× lens and the output beam is imaged onto an InGaAs photodetector (or a charge-coupled device camera) also with a 40× lens. Both reference and measurement lights are detected by a dual-channel power meter at the same time. The measured output mode profile is displayed on a video monitor.

For the fabrication of a Mach–Zehnder modulator, a pair of aluminum electrodes of thickness 3000 Å, length 6 mm, and gap 14 μm is formed for electrooptic modulation. The switching voltage measurement setup is also shown in Fig. 1. A triangular voltage signal from the function generator is applied across the electrodes. The input and measured signals were both shown on an oscilloscope which were further used to calculate the switching voltage.

III. RESULTS AND DISCUSSION

The mode profiles are dependent on the strip film thickness τ, waveguide width W, diffusion temperature T, diffusion time t, and operation wavelength λ. As single-mode waveguides are essential for most device applications, only the single-mode waveguides are further discussed latter on. The TE (extraordinary polarization) and TM (ordinary polarization) mode profiles versus different process parameters are shown in Fig. 2. Consider case A as illustrated in Fig. 2. The TE and TM modes show that they have similar guiding profiles. In case B, the TE mode size is slightly larger than that of the TM mode. In case C, the TM mode is not well-confined in the waveguide and most of the power is radiated into the substrate. However, only the TE mode is guided in case D. The above experimental results show that the ZI waveguide supports a single extraordinary or both extraordinary and ordinary polarizations depending on fabrication process parameters. Besides, the single extraordinary polarization waveguide is easier achieved than the single ordinary polarization waveguide due to $\Delta n_e > \Delta n_o$, particularly when fabricated at a lower diffusion temperature [11]. Also, well-confined TE and TM waveguides are more difficult to be obtained when the diffusion temperature is below 900 °C.

In order to further study the polarization-dependent loss, the normalized output power versus different polarizations with some process parameters is shown in Fig. 3. As the incident power is kept constant for any polarizations, the polarization extinction ratio λ is simply defined as $\gamma = 10\log(P_{\rm TE}/P_{\rm TM})$, where $P_{\rm TE}$ and $P_{\rm TM}$ are the output powers of TE and TM modes, respectively. In case D, the best γ obtained is 44 dB at a distance of about 1.5 cm away from the input end of the waveguide and the propagation loss measured by a cut-back method is 0.9 dB/cm. Fig. 4 gives the modulation characteristics curve of a Mach–Zehnder modulator with its waveguides fabricated as those of case D. The measured switching voltage is 17.5 V, the corresponding voltage-length product is 10.5 V-cm, the calculated overlap integral factor by the reported method [12]

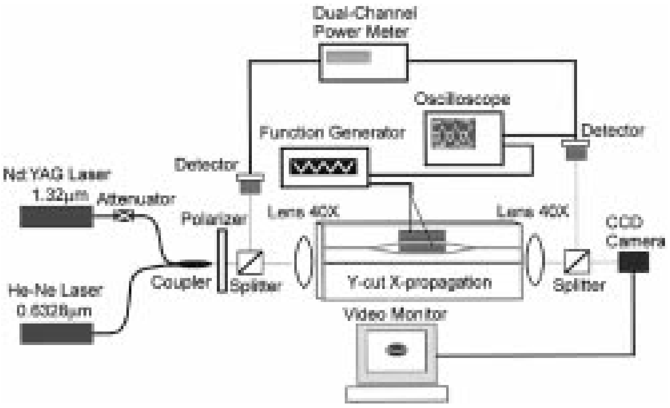

Fig. 1. A schematic diagram of the polarization-dependent loss and switching voltage measurement setup.

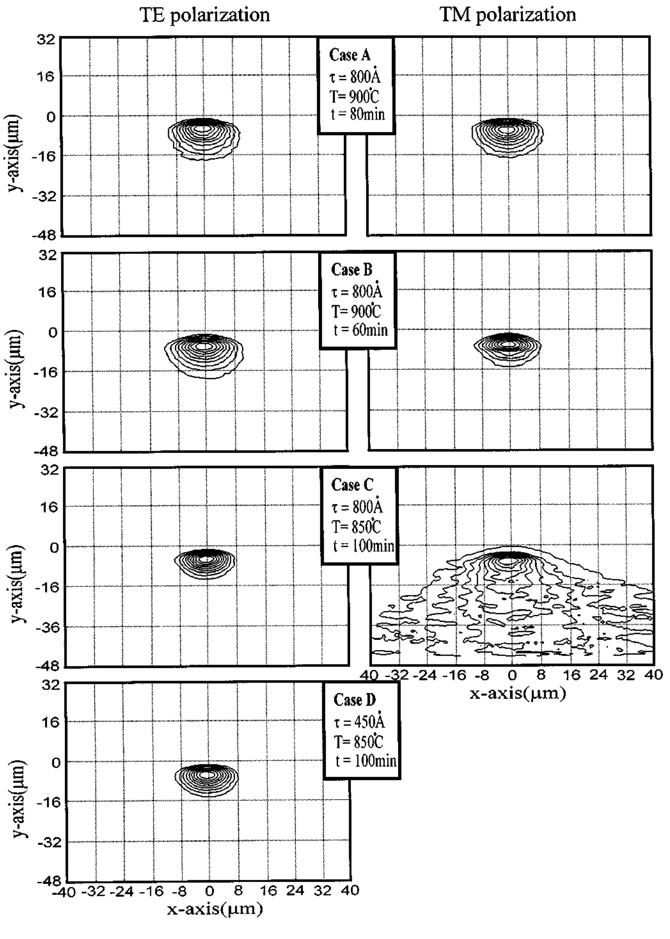

Fig. 2. TE (left) and TM (right) mode profiles versus different process parameters (unguided).

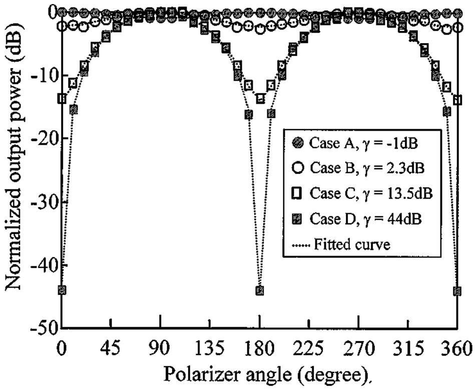

Fig. 3. The normalized output power versus polarization for waveguides fabricated with different process parameters.

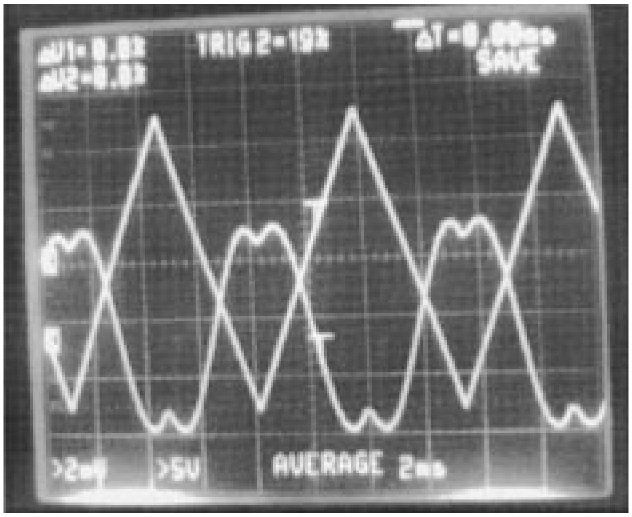

Fig. 4. Measured sinusoidal output signal (2 mV/div) of a zinc indiffusion Mach–Zehnder interferometer with an input saw-tooth wave (5 V/div).

is 0.45. From the above data, the derived r_{33} coefficient is about 30.8 pm/V, which shows that the r_{33} coefficient of a ZI waveguide is not degraded under the specific process condition presented in this work.

IV. CONCLUSION

A polarization-dependent loss measurement of ZI waveguides on a y-cut, x-propagation LiNbO$_3$ substrate for the 1.32-μm wavelength fabricated with different process parameters is firstly and successfully reported. The results show that the ZI waveguide supports a single extraordinary or both extraordinary and ordinary polarizations depending on the process parameters. For the single extraordinary polarization waveguide, the best γ measured is 44 dB and the propagation loss is 0.9 dB/cm. These are all good enough for making a waveguide polarizer. The fabricated ZI Mach–Zehnder modulator also shows that it has a nondegraded electrooptic coefficient r_{33}. With the excellent properties of process-dependent polarization, more flexibility on waveguide device fabrication is of great interest in the near future.

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